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MEASURING THE FLOW OF GASES

THOS. G. ESTEP

Published by
THE BACHARACH INDUSTRIAL INSTRUMENT CO.
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Introduction

The problem of measuring and recording the volume of gases flowing in pipes and ducts is one that is engaging the attention of engineers more and more every day.

In the various industries where gas is used or produced, such as steel plants, producer plants, chemical factories, mines, etc., the management realizes that accurate information concerning the volume of gas used or produced is not only exceedingly valuable in checking operation but in many cases absolutely necessary.

The greatest difficulty with volumetric measurement of gases is that the laws governing the flow of elastic fluids are not generally understood by many engineers and when they are understood, the calculations involved are so long and tedious that they are discouraging.

The object of this pamphlet is to present to those interested, a few of the fundamental principles of the flow of elastic fluids, to facilitate the calculations by means of curves, to show and explain several of the most approved methods of making volumetric measurements and to point out the precautions that must be taken to insure accurate results.

Estimating Pipe Sizes

When it is contemplated to measure the volume of gas passing, it is of the utmost importance that the pipes carrying the gas be of such a size as to permit easy and accurate measurement.

Fortunately the best size of pipe for measuring very nearly coincides with that size which gives minimum cost of investment and operation, for if a pipe be too small, the pressure drop is too great, and if the pipe be too large, the investment cost is too high. The table on the following page shows pipe sizes and their carrying capacity for gases of different density. Whenever a considerable pressure drop can be allowed, the higher velocities, i. e., the pipe sizes at the top of the table should be used, but when only a very small pressure drop is allowable, the pipe sizes at the bottom of the column should be used.

To aid in the selection of the proper pipe size, the following equation is given:

$$V = 66.21\sqrt{\frac{H}{S}}$$

Where V = velocity of gas in the pipe, feet per second.
H = dynamic head, inches of water.
S = specific gravity of the gas.

To use this equation, some value of H will be chosen and the specific gravity will be known. The velocity is then calculated. Knowing the volume in cubic feet per second which the pipe is supposed to carry, divide this volume by the velocity as calculated which gives the area of the pipe in square feet from which the diameter may be found.

TABLE I

Hydro No.	Dynamic Pressure in Inches	Specific Gravity Air=1.0	Velocity Feet per Sec.	THOUSANDS OF CU. FT. PER HOUR AT 62° F. AND 30″ HG. BAROM. PR. PIPE DIAMETER IN INCHES													
				2	4	6	8	10	12	16	20	24	30	36	40	50	60
1	8.0	1.0	187.24	14.7	58.8	132.3	235.3	367.5	529.2	941.0	1470	2117	3310	4765	5882	9195	13234
		.6	241.77	19.0	76.0	170.9	303.8	474.5	683.2	1215.0	1900	2734	4272	6153	7595	11866	17088
		.4	296.08	23.2	93.0	209.3	372.0	581.2	836.7	1488.0	2326	3348	5232	7536	9302	14532	20926
2	4.0	1.0	132.42	10.4	41.6	93.6	166.4	259.9	374.2	665.5	1040	1498	2340	3370	5160	6509	9359
		.6	170.96	13.4	53.7	120.8	214.3	336.0	483.1	859.2	1343	1934	3020	4351	5370	8390	12083
		.4	209.36	16.4	65.8	148.0	262.1	411.0	591.6	1052.2	1644	2368	3700	5328	6577	10275	14797
4	2.0	1.0	93.63	7.4	29.4	66.2	117.8	183.5	264.6	470.6	735	1059	1654	2383	2941	4595	6618
		.6	120.88	9.5	38.0	85.4	151.9	237.3	341.6	607.5	949	1367	2136	3076	3798	5933	8544
		.4	148.04	11.6	46.5	104.6	186.0	290.6	418.4	744.0	1165	1674	2616	3768	4651	7266	10464
8	1.0	1.0	66.21	5.2	20.8	46.8	83.0	130.0	187.5	333.0	520	749	1170	1685	2080	3250	4680
		.6	85.48	6.7	26.8	60.4	107.2	167.8	241.6	429.6	671	967	1510	2175	2685	4195	6042
		.4	104.68	8.2	32.9	74.0	131.5	205.5	295.8	526.1	822	1184	1850	2664	3288	5138	7400
10	.8	1.0	59.22	4.7	18.6	41.8	74.2	116.0	167.4	297.6	465	670	1046	1507	1864	2906	4186
		.6	76.45	6.0	24.0	54.0	96.0	150.0	216.1	384.2	600	865	1350	1946	2402	3752	5403
		.4	93.63	7.4	29.4	66.2	117.6	183.5	264.6	470.6	735	1059	1654	2383	2941	4595	6618
16	.5	1.0	46.82	3.7	14.7	33.1	58.8	91.9	132.3	235.3	368	530	827	1191	1471	2298	3309
		.6	60.44	4.7	19.0	42.7	75.7	118.6	170.8	303.8	475	684	1068	1538	1900	2966	4272
		.4	74.02	5.8	23.2	52.3	92.9	145.3	209.2	372.0	581	837	1308	1883	2325	3633	5232
24	.33	1.0	38.22	3.0	12.0	27.0	47.8	75.0	108.0	192.1	300	432	675	972	1200	1876	2700
		.6	49.35	3.9	15.5	34.9	62.0	96.9	139.5	248.0	388	558	872	1256	1550	2422	3488
		.4	60.24	4.7	18.9	42.4	75.4	118.0	170.0	302.0	472	680	1062	1538	1900	2966	4272
32	.25	1.0	33.10	2.6	10.4	23.4	41.6	65.0	93.5	166.4	260	374	585	842	1040	1624	2340
		.6	42.74	3.4	13.4	30.2	53.5	83.9	120.8	214.8	336	483	755	1088	1342	2097	3021
		.4	52.34	4.1	16.4	37.0	65.7	102.7	147.9	263.0	411	592	925	1332	1644	2569	3700
50	.16	1.0	26.48	2.1	8.3	18.7	33.3	52.0	74.8	133.3	208	299	468	674	834	1300	1872
		.6	34.19	2.7	10.7	24.2	42.9	67.1	96.6	171.8	268	386	604	870	1074	1678	2417
		.4	41.87	3.3	13.2	29.6	52.5	82.2	118.3	210.7	329	473	739	1065	1315	2055	2959

Attention is called to the fact that the above equation is correct for one condition only, viz., when the gas has a temperature of 62 degs. F. and a pressure of 30″ Hg. absolute, but for the other temperatures and pressures usually encountered in practice, the equation will give results close enough for estimating purposes.

Table 1 is prepared from the above equation to facilitate the work of estimating.

The theory and practice of the measurement of the flow of gases in pipes and ducts will now be taken up.

General Equations for Flow

Almost any text book on Thermodynamics will show the derivation of the following equation for the flow of elastic fluids through orifices or short tubes.

$$W_2^2 - W_1^2 = 2g \frac{n}{n-1} RT_1 \left[1 - \left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} \right] \qquad (1)$$

W_1 = velocity at section F_1, feet per second. Fig. (1)

W_2 = velocity at section F_2, feet per second. Fig. (1)

g = acceleration due to gravity, feet per second per second.

n = ratio of specific heat at constant pressure to specific heat at constant volume for gases. n, for vapors depends upon the conditions and can be determined, at least approximately.

R = gas constant, foot pounds per degree F.

T_1 = temperature of gas at section F_1, Fig. (1) degs. F. absolute, equals observed temperature plus 459.6.

P_1 = pressure at section F_1, pounds per sq. foot absolute. Fig. (1)

P_2 = pressure at section F_2, pounds per sq. foot absolute. Fig. (1)

The above equation is based on the assumption that the flow is frictionless and that the expansion of the gas from P_1 to P_2 is without heat exchange and without friction.

For the present, we will assume that $W_1 = 0$, that is, that the velocity of approach can be neglected.

If M = weight of gas flowing, pounds per second.

F_2 = area of orifice in sq. feet.

V_1 = specific volume of gas at section F_1, cubic feet per pound. Fig. (1)

V_2 = specific volume of gas at section F_2, cubic feet per pound. Fig. (1)

Then the law of continuity of flow is

$$M V_2 = F_2 W_2 \qquad (2)$$

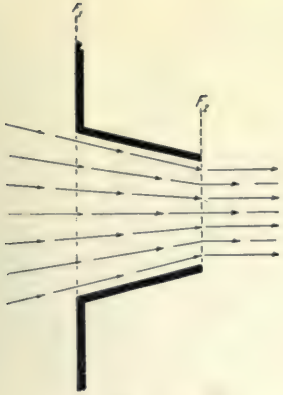

Fig. (1)

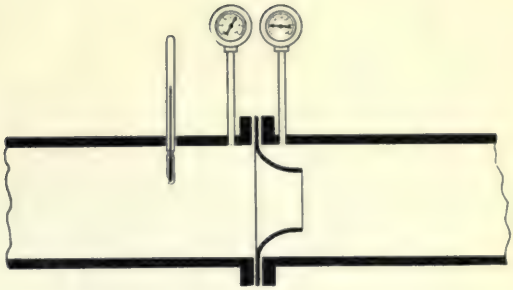

Fig. (2)

Also from the adiabatic law

$$V_2 = V_1 \left(\frac{P_1}{P_2}\right)^{\frac{1}{n}} \tag{3}$$

Combining equations (2) and (3) with equation (1) and solving for M, we have:

$$M = \frac{F_2}{1} \frac{P_1}{T_1} \sqrt{2g \frac{n}{n-1} \frac{1}{R} \left[\left(\frac{P_2}{P_1}\right)^{\frac{2}{n}} - \left(\frac{P_2}{P_1}\right)^{\frac{n+1}{n}} \right]} \tag{4}$$

This is the general equation for flow, assuming that the velocity of approach is zero.

An examination of this equation shows that when p_2 equals p_1, then M equals zero, which is as it should be. But if p_2 equals zero, then M equals zero also, which means that no fluid can be discharged into a perfect vacuum, a result that is manifestly absurd. Experiment shows that under certain conditions, the pressure p_2 at the mouth of the orifice is not equal to the pressure in the region into which the jet discharges and that at some point the flow becomes a maximum and remains constant at that no matter how much the pressure in the region into which the jet discharges is reduced below that point. In other words, there is some ratio of $\frac{p_2}{p_1}$ that will make the flow a maximum. By well known methods of calculus, it can be shown that the ratio which makes the flow a maximum is

$$\frac{P_2}{P_1} = \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}$$

This is called the critical ratio and when $n = 1.4$ as for air, then $\frac{p_2}{p_1} = .53$. This means that so long as the ratio $\frac{p_2}{p_1}$ is equal to or greater than the

critical, the pressure p_2 is equal to the pressure in the region into which the jet discharges but when this ratio is less than the critical, the pressure p_2 is not equal to the pressure in the region into which the jet discharges but becomes some function of p_1 (for air, $.53p_1$) and remains constant at this, no matter how much the pressure in the region into which the jet discharges is reduced.

In actual practice, it is comparatively simple to obtain the necessary data for the solution of equation (4). For gas flowing in a pipe at relatively high pressure, an arrangement similar to Fig. (2) can be used.

A standard orifice is placed between flanges in a section of straight pipe, two pressure gages are installed, one on each side of the orifice and a thermometer is placed in the flow preceding the orifice. These three readings along with the area of the orifice are sufficient to make the calculation from equation (4).

This equation is rather tedious to solve due to the fractional exponents but its solution can be simplified by means of a curve. Suppose we let

$$K=\sqrt{2g\frac{n}{n-1}\frac{1}{R}\left[\left(\frac{p_2}{p_1}\right)^{\frac{2}{n}}-\left(\frac{p_2}{p_1}\right)^{\frac{n+1}{n}}\right]} \tag{5}$$

and take successive values of $\frac{p_2}{p_1}$ and solve for K. Then a curve can be plotted as shown in Fig. (3) with $\frac{p_2}{p_1}$ as abscissa and K as ordinate.

Equation (4) now becomes

$$M=\frac{F_2P_1K}{\sqrt{T_1}} \tag{6}$$

NOTE—In equation (6) F_2 can be taken in square inches if p_1 is taken in pounds per square inch absolute.

Two examples will be given to illustrate the use of this curve, based on the arrangement shown in Fig. 2.

EXAMPLE 1—Suppose that air is flowing in the pipe and that the two pressure gages read 60 and 50 pounds per square inch or 74.7 and 64.7 pounds per square inch absolute. Let the temperature be 70 degrees F. or 70 plus 459.6 equals 529.6 degrees F. absolute. The area of the orifice is 2 square inches.

From the above $\frac{p_2}{p_1}=.866$. From the curve, $K=.370$.

Then

$$M=\frac{2\times74.7\times.370}{\sqrt{529.6}}=2.4 \text{ pounds per second.}$$

EXAMPLE 2—Suppose that the conditions are the same as in example 1 except that p_2 is atmospheric or 14.7 pounds per sq. in. absolute. In this case $\frac{p_2}{p_1}=.197$. This ratio is less than the critical so that it can

CURVE OF K (COEFFICIENT)
FOR FLOW OF
AIR AND BLAST FURNACE GAS
THROUGH STANDARD ORIFICES

$$W = \frac{A P_1 K}{\sqrt{T}}$$

W = WEIGHT OF GAS FLOWING - LBS. PER SECOND

A = AREA OF ORIFICE - SQ. IN.

K = COEFFICIENT FROM CURVE

P_1 = PRESSURE OF GAS PRECEEDING ORIFICE - LBS. PER SQ. IN.

P_2 = PRESSURE OF GAS FOLLOWING ORIFICE LBS. PER SQ IN.

T = ABSOLUTE TEMP. OF GAS PRECEEDING ORIFICE - DEGS. F.

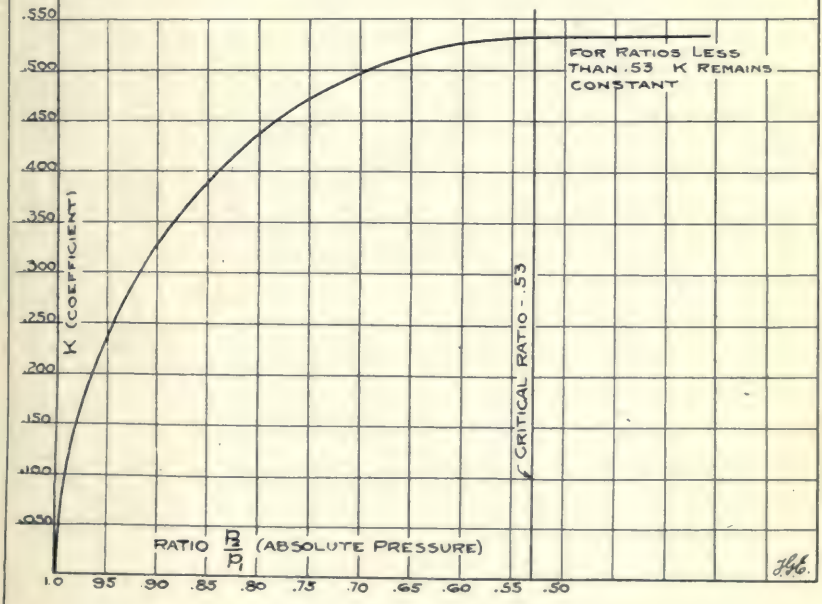

Fig (3)

be ignored and the critical ratio used which is .53 for which K = .532. Then

$$M = \frac{2 \times 74.7 \times .532}{\sqrt{529.6}} = 3.45 \text{ pounds per second.}$$

Equation (6) gives the quantity flowing in pounds. It is often desired to know the volume at the initial temperature and pressure rather than the weight. In that case

$$V = .37 F_2 K \sqrt{T_1}$$

Where V = volume flowing at initial temperature and pressure, cubic feet per second.

F_2 = area of the orifice in square inches.

K and T_1 as above.

This method is particularly adapted to measuring gases at fairly high pressures, such as the discharge from compressors and blowing engines. The curve given is for air and blast furnace gas. Curves have been prepared for by-product coke oven gas, natural gas, oxygen, hydrogen, nitrogen and carbon dioxide and will be gladly furnished on request.

In all of the above equations it was assumed that the velocity of approach was zero and that the co-efficient of discharge for the orifice was unity. These two assumptions are not correct but one error can be made to compensate for the other as will be shown under the discussion of standard orifices.

Measurement of Gases at or Near Atmospheric Pressure

Equation (4) is a general equation and applies to measuring gases at any pressure, but where the difference in the pressure on the two sides of the orifice is small, as it is in most cases, then a much simpler equation may be used by making the assumption that there is no change in the specific volume of the gas due to the change in pressure. This assumption is permissible because in most cases the change in pressure is less than one inch of water and the error introduced by this assumption is well within the limits of accuracy of any measuring device.

Assuming then that the gas maintains a constant specific volume as it passes through or by the measuring device, the velocity of flow becomes

$$V = \sqrt{2gh} \qquad (7)$$

Where V = velocity of gas in feet per second.

g = acceleration due to gravity, feet per second per second.

h = velocity or dynamic head in feet of the fluid being measured.

After the velocity of the gas through a section of known area is determined, it is a very simple matter to find the volume flowing. It only remains then, to produce in some manner a velocity or dynamic head h which can be measured.

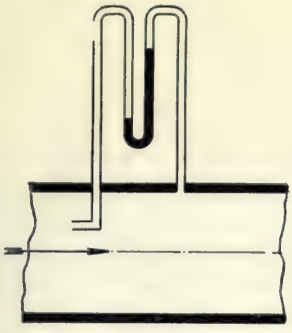

Fig (3)

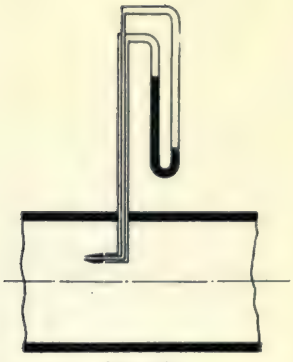

Fig (4)

Four methods of doing this will be given;

1. By means of an impact tube placed in a section of straight pipe as shown in Fig. 3 or by means of a combined impact and static pressure tube, called a Pitot tube, as in Fig. 4.

2. By placing a thin plate orifice in the pipe between flanges as shown in Fig. 5, measuring the drop in pressure as the gas passes through.

3. By placing a standard or well rounded orifice in the pipe between flanges as shown in Fig. 6.

4. By a combination of the standard orifice and the Pitot tube as shown in Fig. 7.

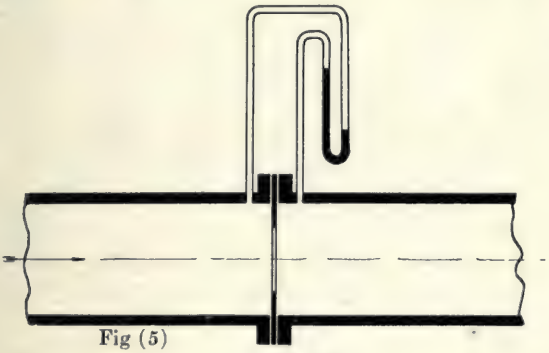

Fig (5)

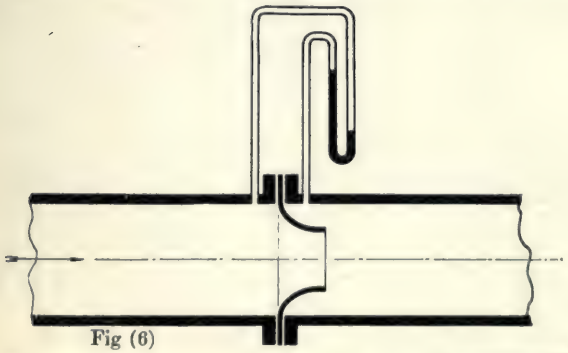

Fig (6)

These four methods will be discussed in detail later.

It is to be noted that in all four cases, the quantity to be measured is the dynamic head h. For practical reasons, this quantity is kept small, usually not over one inch of water.

Assuming then that it is measured in inches of water, it must be converted into equivalent feet of gas at the temperature and pressure in the pipe at the point of measurement. To make this conversion it is only necessary to divide h as measured by 12 and multiply by the ratio of densities of gas and water.

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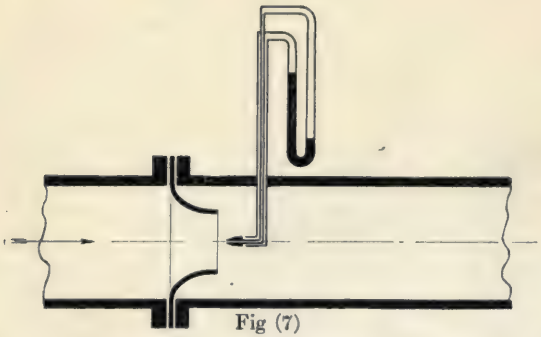


Fig (7)

This sounds simple enough but some confusion exists here because the two terms, density and specific gravity are used rather loosely by many engineers. Density can, in its true sense, mean but one thing, pounds per cubic foot (in English units), while specific gravity is a ratio of densities and for perfect gases it simply becomes the ratio of the gas constants, which ratio is constant for any combination of temperature and pressure.

The true specific gravity of a gas is the ratio of the density of the gas to the density of air, both gas and air being at the same temperature and pressure.

A great deal of confusion exists because it is the practice among gas engineers to define specific gravity as the ratio of the density of the gas at any condition of temperature and pressure to the density of air at a fixed condition of temperature and pressure taken as a standard. It is evident then, that if this latter definition is to be used, the temperature and pressure of both the gas and the air must be stated or else the figures given for the specific gravity become meaningless. For this reason it would be well if engineers would drop specific gravity as a method of defining gases and use density instead. However, since the last mentioned method of defining specific gravity is the one used at present, that definition will be assumed in the following discussion, that is, the density of air at a temperature of 62 deg. F. and an absolute pressure of 30 inches of mercury will be taken as unity and the temperature and pressure of the gas in question will be stated. In other words, in the following, specific gravity will mean the ratio of the density of the gas at any given temperature and pressure to the density of air at 62 deg. F. and 30 inches of mercury.

The gas being measured is very rarely at 62 degrees F. and 30″ Hg. so to find the specific gravity at any other temperature and pressure, referred to air at 62 degrees F. and 30″ Hg. as unity, the following equation may be used.

$$\text{Specific gravity at any temperature and pressure} = \frac{927.4P}{R \times T} \qquad (8)$$

Where P = gas pressure in inches of mercury.

R = gas constant in English units.

T = absolute temperature of the gas, degrees F.

If the specific gravity of the gas at 62 degrees F. and 30″ Hg. is known, the following equation will give the specific gravity at any other temperature and pressure, air at 62 degrees F. and 30″ Hg. = 1.

$$\text{Specific gravity at any other temperature and pressure} = S\left(\frac{17.39P}{T}\right) \qquad (9)$$

Where S = specific gravity at 62 degrees F. and 30″ Hg.

P = absolute gas pressure in inches of mercury.

T = absolute temperature of the gas, degrees F.

The following table gives the values of the gas constant R and the specific gravity at 62 degrees F. and 30″ Hg. of the common gases, the values for the mixed gases being based on average analysis. To insure accuracy in measuring mixed gases, the analysis should be definitely known.

Name of Gas	Gas Constant R	Specific Gravity
By-Product Coke Oven Gas	143.90	.3707
Natural Gas	93.96	.5677
Blast Furnace Gas	52.06	1.0245
Nitrogen	54.99	.9700
Oxygen	48.25	1.1055
Hydrogen	765.86	.0696
Carbon Dioxide	35.09	1.5201
Carbon Monoxide	55.14	.9673
Air	53.34	1.0000
Methane	96.31	.5412
Nitric Oxide	51.40	1.0377

With the aid of equations (8) and (9), the specific gravity of the gas can easily be calculated for any condition of temperature and pressure.

In all of the above discussion of specific gravity, we have assumed that the gas is dry, that is, free from water vapor. In a great many cases in practice, the gas is either saturated or partially saturated with water vapor. By-product coke oven gas and blast furnace gas are usually saturated while air supply to compressors is only partially saturated depending upon the relative humidity as determined by the hygrometer.

The chemist always reports the specific gravity of dry gas so that if water vapor is present in the gas being measured, it is necessary to calculate the specific gravity at the temperature, pressure and degree of saturation at the point of measurement.

We will now illustrate how this calculation is made by a concrete example rather than by equations. According to Dalton's law for mixed gases, when two or more gases are mixed and have no chemical action on each other, the total pressure exerted by the mixture is equal to the sum of the partial pressures of each gas in the mixture. Hence, if we have a mixture of gas and water vapor, the total pressure indicated is the sum of the pressure of the gas and the pressure of the water vapor. If the gas be saturated with water vapor, the vapor pressure is that corresponding to the temperature of the mixture and can be found from any tables giving the properties of saturated steam.

Suppose that our actual problem is as follows: specific gravity of dry gas at 62 degrees F. and 30″ Hg. is .4 referred to air at the same temperature and pressure as unity. This gas at the point of measurement has a temperature of 90 degrees F. and a pressure of 30″ Hg. and is saturated with water vapor. What is the specific gravity of the mixture under these conditions, referred to air as unity at 62 degrees F. and 30″ Hg?

From Marks & Davis Steam Tables, we find that at 90 degrees F. the vapor pressure is 1.417″ Hg. and the weight of one cubic foot of the vapor is .002131 pounds.

$30 - 1.417 = 28.583$″ Hg. = pressure of gas in the mixture.

$90 + 459.6 = 549.6$ degrees F. absolute.

$62 + 459.6 = 521.6$ degrees F. absolute.

.076265 = weight of one cubic foot of air at 62 degrees F. and 30″ Hg.

$.076265 \times .4 = .030506$ = weight of one cubic foot of dry gas at 62 degrees F. and 30″ Hg.

$\frac{.030506 \times 521.6}{549.6} = .028952$ = weight of one cubic foot of dry gas at 90 degrees F. and 30″ Hg.

$\frac{.028952 \times 28.583}{30} = .027584$ = weight of one cubic foot dry gas at 90 degrees F. and 28.583″ Hg.

$.027584 + .002131 = .029715$ = weight of one cubic foot of mixture of gas and water vapor at 90 degrees F. and 30″ Hg.

$\frac{.029715}{.076265} = .3896$ = specific gravity of the mixture at 90 degrees F. and 30″ Hg. and saturated with water vapor.

To save the labor of all this calculation, the curves shown in Fig. 8 have been plotted for gases saturated with water vapor at 30″ Hg. so that such problems can be solved at a glance.

The problem just solved was for a gas saturated with water vapor. In case the gas is not completely saturated, as the air supplied to an air compressor or turbo blower, the procedure is as follows. Determine the degree of relative saturation in the usual manner. Then consult a hygrometric table and find the weight of moisture in one cubic foot of gas at the observed temperature and relative humidity. By means of the same table, find the temperature at which the gas will have the same weight of water vapor when saturated, in other words, find the dew point temperature. Then take the vapor pressure and density at the dew point temperature and proceed as above. When a gas is not saturated, the water vapor is in a superheated condition so that the dew point or saturation temperature must be found and used.

Specific gravity instead of density is used in actual practice and since from the foregoing, the specific gravity under any conditions can be found, the formula for velocity will now be modified as follows:

$$V = 66.21\sqrt{\frac{H}{S}} \qquad (10)$$

Where V = velocity of gas in feet per second.

H = dynamic head in inches of water.

S = specific gravity of gas referred to air as unity at 62 degrees F. and 30″ Hg.

The constant 66.21 results from inserting the numerical values for the density of air and water and for the acceleration of gravity.

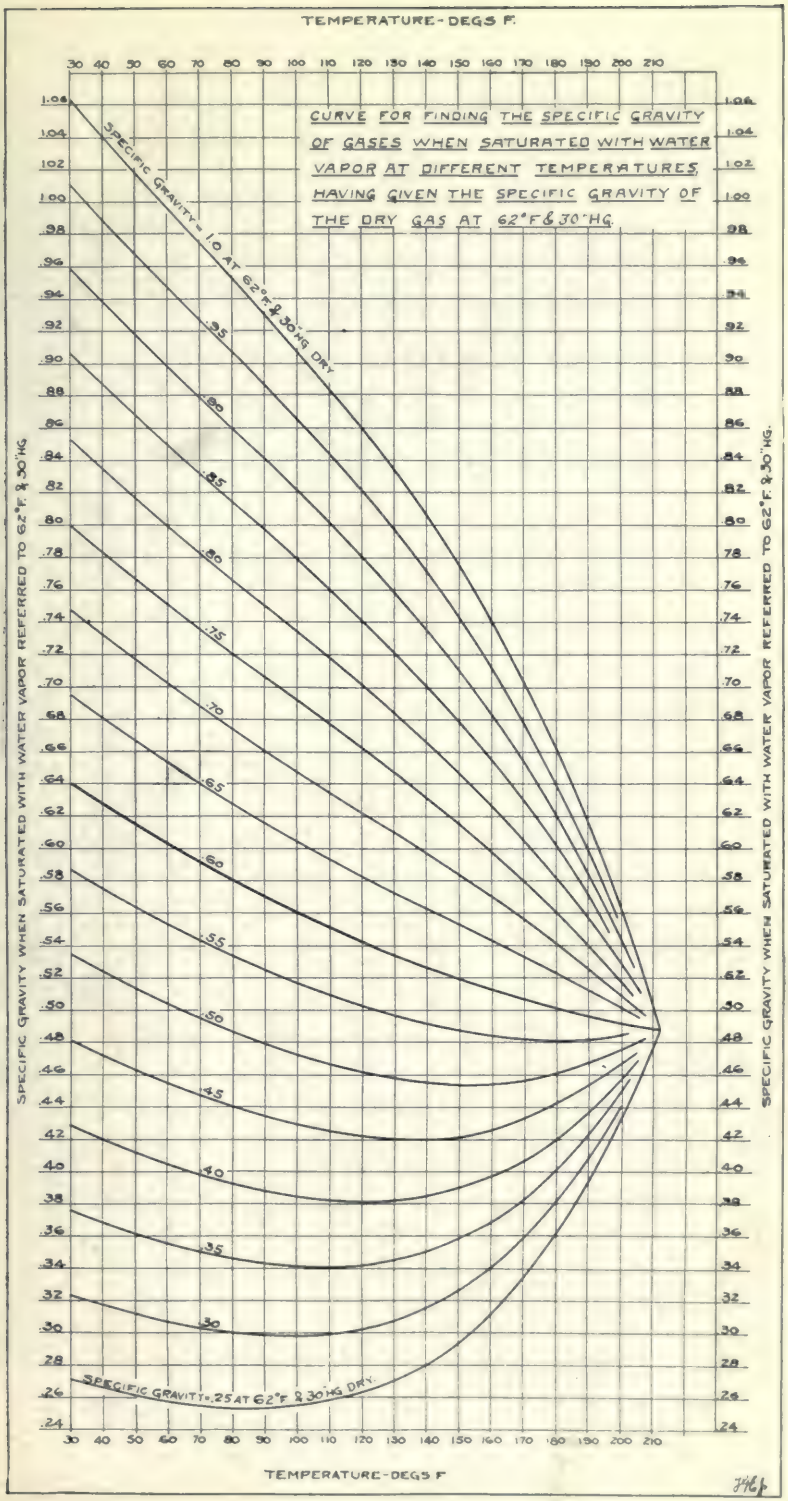

TEMPERATURE - DEGS F.
CURVE FOR FINDING THE SPECIFIC GRAVITY OF GASES WHEN SATURATED WITH WATER VAPOR AT DIFFERENT TEMPERATURES, HAVING GIVEN THE SPECIFIC GRAVITY OF THE DRY GAS AT 62°F & 30" HG.
SPECIFIC GRAVITY = 1.0 AT 62°F & 30" HG DRY
.95
.90
.85
.80
.75
.70
.65
.60
.55
.50
.45
.40
.35
.30
SPECIFIC GRAVITY = .25 AT 62°F & 30" HG DRY.
SPECIFIC GRAVITY WHEN SATURATED WITH WATER VAPOR REFERRED TO 62°F & 30" HG.
SPECIFIC GRAVITY WHEN SATURATED WITH WATER VAPOR REFERRED TO 62°F & 30" HG.
TEMPERATURE - DEGS F

Figure (8)

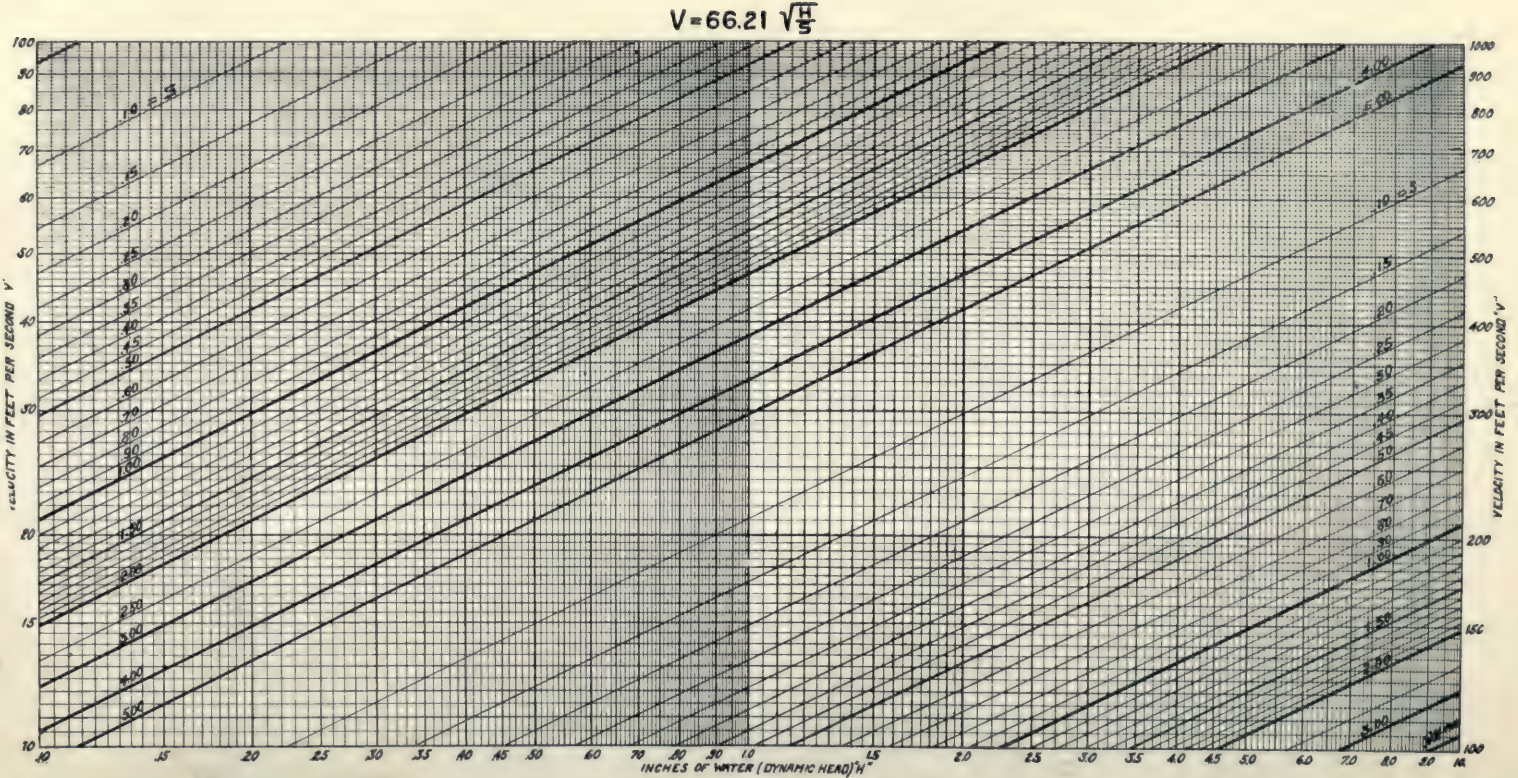

V=66.21 √H/S
VELOCITY IN FEET PER SECOND "V"
INCHES OF WATER (DYNAMIC HEAD) "H"

Figure (9)

It must be kept in mind that S in this equation is the specific gravity of the fluid flowing in the pipe at the temperature and pressure at the point of measurement referred to air at 62 degrees F., and 30″ Hg. as unity. If the gas, at the point of measurement contains water vapor, then S is the specific gravity of the mixture.

Equation (10) has been plotted as shown in Fig. 9, logarithmic paper being used so that straight lines would obtain. This permits the reading of the velocity directly for any differential pressure and specific gravity provided the conditions are the same as those for which the curve was plotted.

Having the velocity from the above equation or curve, if we multiply by the area of the orifice or pipe, the result is the volume of the fluid flowing at the pressure and temperature at the point of measurement; if the gas is dry, it will be the volume of dry gas; if the gas contains water vapor, it will be the volume of the mixture.

Since the volume calculated in the above manner will be the volume at the pressure and temperature at the point of measurement, it may be desired to convert this to equivalent volume at some other temperature and pressure. If the gas is dry, this is very simple. Multiply the calculated volume by the ratio of absolute temperatures and ratio of absolute pressures, the volume varying directly as the temperature and inversely as the pressure.

If the gas contains water vapor, it may be desired to know the volume of dry gas. To find this, multiply the volume of the mixture by the ratio of the absolute gas pressure to the absolute pressure of the mixture in the pipe. The volume can be reduced to dry gas at some other temperature by further multiplying by the ratio of absolute temperatures.

It may also be desired to reduce the volume of gas saturated with water vapor at the temperature and pressure at the point of measurement to volume of gas saturated with water vapor at some other temperature and pressure as standard, say 62 degrees F. and 30″ Hg. To do this, multiply the volume of mixture flowing under actual conditions by the ratio of the absolute temperature at standard conditions to the absolute temperature at the point of measurement and also by the ratio of the absolute gas pressure under the actual conditions to the absolute gas pressure under standard conditions, the absolute gas pressure in each case being the pressure of the mixture minus the vapor pressure.

These various reductions will now be illustrated by examples. Suppose that a gas having a specific gravity of .4 at 62 degrees F. and 30″ Hg. referred to air at the same temperature and pressure as unity is flowing in a pipe. The gas is saturated with water vapor and at the point of measurement has a temperature of 90 degrees F. and a pressure of 30″ Hg. To find the specific gravity under the actual conditions, the calculations are the same as those given on page 11 or can be taken from the curve Fig. 8, which gives the specific gravity as .3896. This value, along with that for dynamic head inserted into the equation for velocity and the velocity multiplied by the area of the orifice in square feet will give, say, a volume of 100 feet per second. This means that there are 100 cubic feet at 90 degrees F. and 30″ Hg. of a mixture of gas and water vapor. The volume of dry gas at 90 degrees F. and 30″ Hg. is

$$100 \times \frac{28.583}{30} = 95.28 \text{ cubic feet}$$

The volume of dry gas at standard conditions of 62 degrees F. and 30″ Hg. is as follows:

$$100 \times \frac{28.583}{30} \times \frac{521.6}{549.6} = 90.5 \text{ cubic feet.}$$

The volume of gas saturated with water vapor at standard conditions of 62 degrees F. and 30″ Hg. is as follows, the vapor pressure at 62 degrees F. being .56″ Hg.

$$100 \times \frac{521.6}{549.6} \times \frac{28.583}{29.44} = 92.3 \text{ cubic feet.}$$

The four methods for producing dynamic head already mentioned will now be taken up in detail.

Pitot Tubes

The principle involved in the Pitot tube was used as early as 1730 by Henri Pitot. Since that time it has been subjected to countless tests and has always proven its accuracy when constructed and used properly.

When a simple bent tube is used as in Fig. 3 it is usually given the name of impact tube. The only objection to this arrangement is the uncertainty about the size, shape and location of the static pressure opening. The results of the experiments on this point are not conclusive. To overcome this objection, the so-called Pitot tube is used as shown in Fig. 4 in which the static pressure tube is combined with the impact tube. Various shapes and sizes of static pressure openings in the tube have been carefully investigated and the conclusion is that a round opening of moderate size is the best.

Experiments have also been made to determine if the theoretical formula for velocity is correct for the Pitot tube as used in practice and if it is not, what is the value of the coefficient. The result of all the experiments showed that with a properly constructed tube used in the right manner, the coefficient was unity.

Fig (10)

There are certain precautions which must be taken in the use of the Pitot tube to insure accuracy. It is very important to have the axis of the bent portion of the tube parallel to the stream lines, so as to obtain the true impact and static pressures.

There should be at least 8 diameters of straight pipe of uniform cross section preceding the tube so as to eliminate eddy currents and allow the flow to resolve into parallel stream lines.

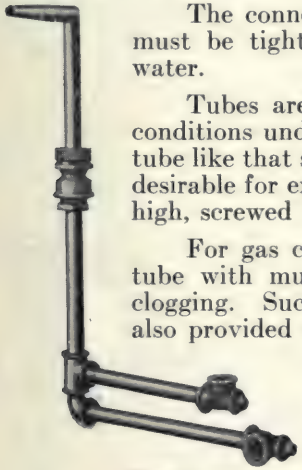
The cross section of the pipe must be accurately determined at the location of the tube and care taken that this section does not change due to foreign matter adhering to the pipe walls.

The temperature and static pressure of the gas in the pipe should be taken as near as possible to the location of the tube. The static pressure may be taken from that portion of the Pitot tube itself instead of through a separate opening.

If the gas contains water vapor and if there is any cooling of the gas as it passes through the pipe, a separator should be placed some distance ahead of the tube so as to remove any suspended particles of water which, if allowed to impinge upon the dynamic opening of the tube would seriously affect the accuracy.

It is necessary to take a series of readings across the diameter of the pipe in order to locate the point of average velocity. The tube can be placed at this point for regular service but the location should be checked from time to time. The location of the tube along the diameter of the pipe is very important when the gas is a mixed one for there is some tendency for the gas to assume a stratified section according to the various densities of the gases in the mixture.

No attempt should be made to measure a pulsating flow without first removing the pulsations by throttling or the use of receivers or both.



(Fig 11)

The connections from the tube to the measuring device must be tight, and free from pockets which might collect water.

Tubes are made in various forms, depending upon the conditions under which they are used. If the gas is clean, a tube like that shown in Fig. 10 is used. This form is also very desirable for experimental work. If the pressure of the gas is high, screwed connection can be used.

For gas containing foreign matter such as dust, etc., a tube with much larger openings must be used to prevent clogging. Such a tube is shown in Fig. 11. Connections are also provided so that compressed air or steam can be blown through the tube to clean it when necessary.

A special type of tube is made for measuring gases containing tar, such as producer gas. It contains a coil of wire which is electrically heated, thus preventing the collection of tar.

The Pitot tube is not adapted to measuring very low velocities. A gas having a specific gravity of 1 flowing at 20 feet per second will show a dynamic head of about .1 inch of water. By using a differential pressure gage of large magnifying power, velocities somewhat less than this can be measured accurately but it is better, where possible, to secure a higher dynamic reading. To meet this condition the double bent tube is used as shown in Fig. 12. This magnifies the velocity head by 1.37 for the gases usually measured, thus permitting the measuring of lower velocities.

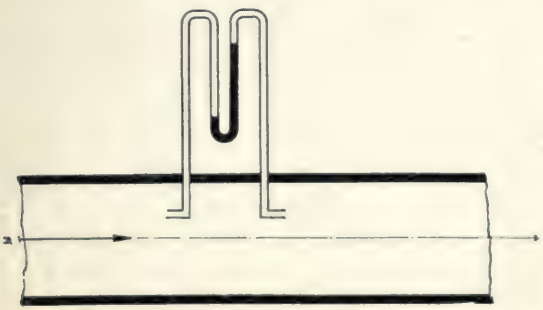


Fig (12)

Problems do occur in practice, however, where the velocity is so low that even the double bent tube will not answer. If it is not permissible to increase the velocity by reducing the section, then a tube arranged as shown diagrammatically in Figs. 13 and 14 is used. The actual construction is not shown because each tube is designed to meet the particular condition presented. This type of tube increases the velocity step by step until it can be measured accurately. Each tube is carefully tested before installation to determine the magnification. Tubes have been made which increase the velocity head 3.5 times.

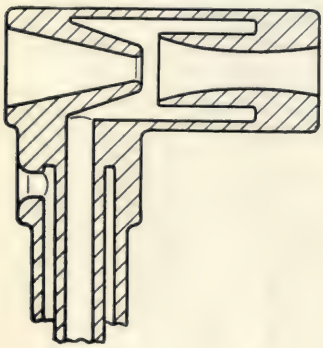


Fig (13)

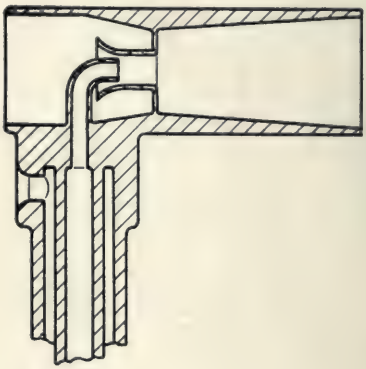
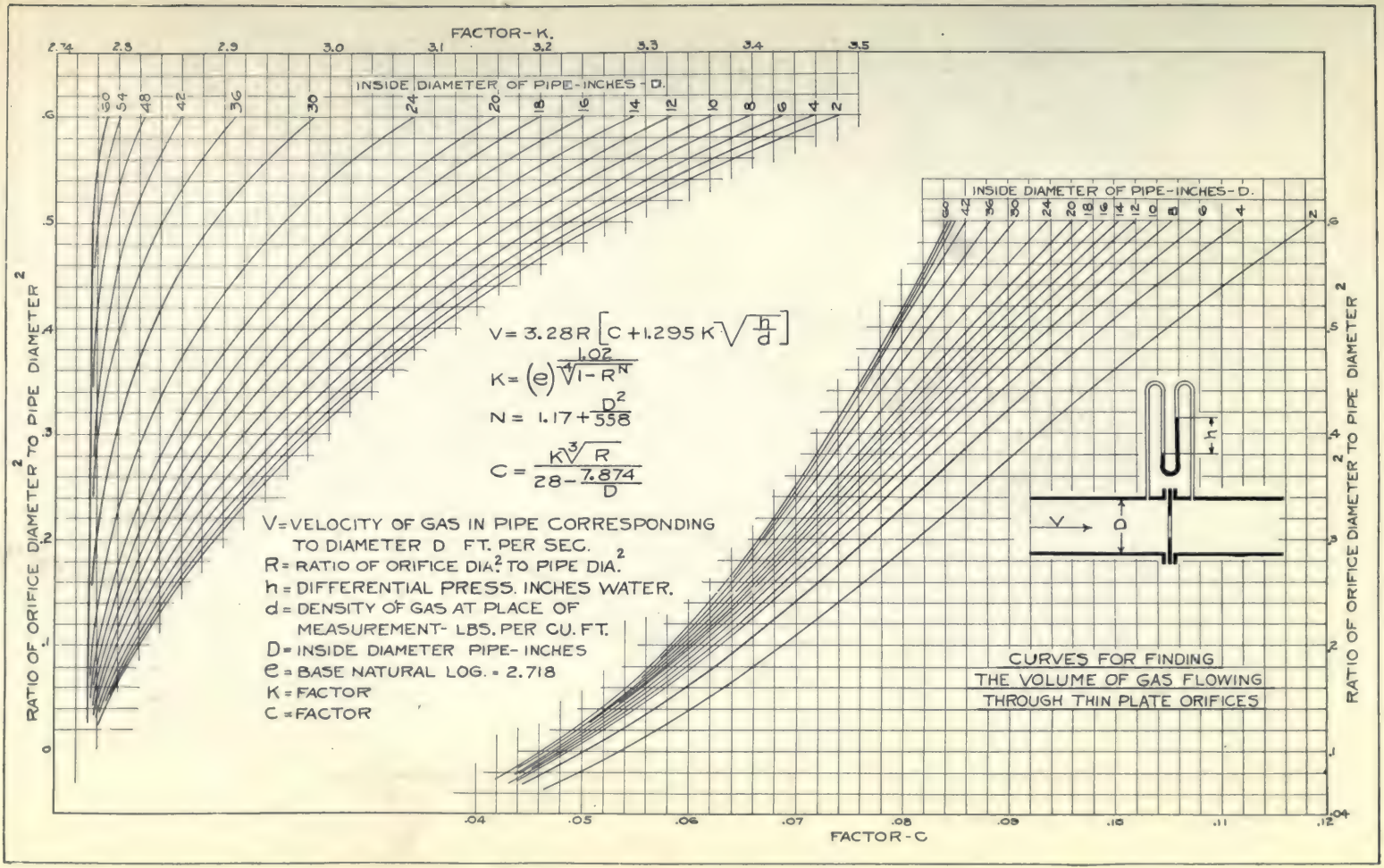


Fig (14)

Thin Plate Orifice

Measuring gases with the thin plate orifice as illustrated in Fig. 5 has the advantage that the orifice is easily made and installed, but there are two disadvantages: first, there is a loss in pressure as the gas passes through, very little of which is regained later. In most cases the small loss in pressure is not important but there are cases where even a slight drop in pressure is not permissible, and the thin plate orifice cannot be considered. The second disadvantage of the thin plate orifice is that there is a large contraction of the jet which varies with the ratio of the orifice diameter to pipe diameter. Further, the differential pressure as measured represents the amount of pressure converted into velocity, and the velocity calculated from this quantity is the velocity in the orifice due to the pressure drop only. But the gas approaches the orifice with a certain velocity which must be added to the calculated orifice velocity. Therefore, the theoretical equation for velocity must be multiplied by a coefficient to take care of contraction and velocity of approach. The disadvantage arises from the fact that this coefficient is a variable quantity, depending upon the rate of flow and the ratio of orifice diameter to pipe diameter.

It would appear then, that to get satisfactory results with the thin plate orifice method, it would be necessary to calibrate each installation under the actual conditions that obtain. This, however, is not necessary. The results of a very exhaustive series of experiments on thin plate orifices have been given in an empirical equation which is given


FACTOR-K.
INSIDE DIAMETER OF PIPE-INCHES-D.
RATIO OF ORIFICE DIAMETER TO PIPE DIAMETER²
FACTOR-C
$V = 3.28R\left[C + 1.295K\sqrt{\frac{h}{d}}\right]$
$K = (e)^{\frac{1.02}{\sqrt[4]{1-R^4}}}$
$N = 1.17 + \frac{D^2}{558}$
$C = \frac{K\sqrt[3]{R}}{28 - \frac{7.874}{D}}$
V = VELOCITY OF GAS IN PIPE CORRESPONDING TO DIAMETER D FT. PER SEC.
R = RATIO OF ORIFICE DIA.² TO PIPE DIA.²
h = DIFFERENTIAL PRESS. INCHES WATER.
d = DENSITY OF GAS AT PLACE OF MEASUREMENT- LBS. PER CU. FT.
D = INSIDE DIAMETER PIPE- INCHES
e = BASE NATURAL LOG. = 2.718
K = FACTOR
C = FACTOR
V
D
h
CURVES FOR FINDING THE VOLUME OF GAS FLOWING THROUGH THIN PLATE ORIFICES

below. This equation was checked very carefully at the laboratory of the Carnegie Institute of Technology and was found to be correct at points checked. The equation is as follows:

$$V = 3.28\ R\left[C + 1.295K\sqrt{\frac{h}{d}}\right] \tag{11}$$

$$K = e^{\sqrt{\frac{1.02}{1-R^N}}} \tag{12}$$

$$N = 1.17 + \frac{D^2}{558} \tag{13}$$

$$C = \frac{K\sqrt{R}}{28 - \frac{7.874}{D}} \tag{14}$$

Where V = velocity of the gas in the main pipe at point of measurement, feet per second.

R = ratio of orifice area to pipe area.

h = differential pressure in inches of water.

d = density of the gas being measured at the pressure and temperature at point of measurement, pounds per cubic foot.

D = inside diameter of main pipe in inches.

e = base of natural logarithms = 2.718.

K and C are factors as shown.

This equation is somewhat tedious to solve, hence the curves shown in Fig. 15 are given which greatly facilitate the solution and are self explanatory.

In using this equation, note carefully that V is not orifice velocity but the velocity in the main pipe. The general precautions given for the use of the Pitot tube apply to the use of the thin plate orifice.

Standard Orifice

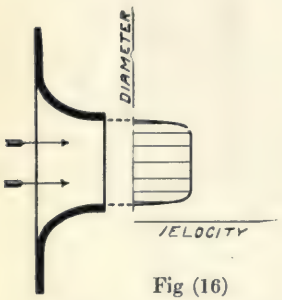


Fig (16)

The well rounded orifice shown in Fig. 6, usually called the standard orifice is coming into very general use for measuring gases, particularly on account of its simplicity and accuracy. Aside from being very easily installed, it has the further advantage that the coefficient is nearly constant over a wide range of conditions, varying from .975 for small orifices to .99 for large ones. The only reason the coefficient is not unity is due to the friction of the gas on the walls of the orifice. This causes a falling off in velocity at the periphery of the orifice as shown in Fig. 16. In large orifices, this loss of velocity is less proportionally than for small orifices. Also a large part of the velocity head or differential pressure is converted into static pressure again after passing the orifice. Thus the resulting pressure drop is very small, permitting the use of the standard orifice in almost any case that might arise.

The question is often asked, however, what is the loss of head or pressure due to the insertion of such an orifice in the pipe line? A great many years ago Carnot proposed the following equation for this loss:

$$H = \frac{(W_2 - W_1)^2}{2g} \tag{15}$$

Where H = lost head in feet of the fluid being measured.

W_1 = velocity of fluid in the pipe preceding the orifice, feet per second.

W_2 = velocity of fluid in the orifice due to the differential pressure, feet per second.

g = acceleration due to gravity, feet per second per second.

Careful tests were made at the Carnegie Institute of Technology to verify this equation and it was found to give the loss very closely. At low velocities the result from the equation is a little high and at high velocities a little low. The only factor unaccounted for is the velocity of approach, for as in the thin plate orifice, the differential pressure as measured gives the velocity due to this pressure drop only and the initial velocity should be added to this to give correct orifice velocity. This factor can be eliminated very easily as will be shown.

Referring again to equation (1), which is the exact theoretical equation for flow, let the right hand member of this equation equal C. Then,

$$W_2^2 - W_1^2 = C \tag{16}$$

If A_1 = area of main pipe,

A_2 = area of orifice.

Then if there is no change in specific volume as the gas flows through the orifice

$$W_1 A_1 = W_2 A_2 \tag{17}$$

or

$$W_1 = \frac{W_2 A_2}{A_1} \tag{18}$$

Substituting this value of W_1 in equation (16) and solving for W_2, we have:

$$W_2 = \sqrt{\frac{C}{1 - \left(\frac{A_2}{A_1}\right)^2}} \tag{19}$$

Since the coefficient of discharge for the standard orifice is about .98, the right hand member of equation (19) must be multiplied by .98 to give the actual value of W_2 and the equation becomes:

$$W_2 = .98 \sqrt{\frac{C}{1 - \left(\frac{A_2}{A_1}\right)^2}} \tag{20}$$

If we now select the proper ratio of areas A_2 and A_1, it is possible to have the denominator of the fraction under the radical cancel the coefficient of .98 outside the radical. The proper area ratio to do this is .2, which means that if the orifice diameter is approximately .45 of the pipe diam-

eter, the velocity of approach and the coefficient of discharge may be neglected and the equation for actual velocity of flow becomes

$$W_2 = 1\ C \tag{21}$$

Or, if the differential pressure is small so that changes in specific volume of the gas due to the difference in pressure may be neglected, then,

$$W_2 = 66.21 \sqrt{\frac{H}{S}} \tag{22}$$

Under the same conditions as given for equation (10).

Standard orifices can be made any size and of the proper shape so that the coefficient will be within the limits mentioned.

Standard Orifice and Pitot Tube

Certain cases arise in practice where a combination of the standard orifice and the Pitot tube as shown in Fig. 7 will best meet the conditions. The function of the orifice in this case is to straighten the stream lines and make them parallel, to increase the velocity so that it can be readily and accurately measured and to remove the necessity of making a traverse of the pipe to find the point of average velocity.

Tests have shown that the velocity of the issuing jet is constant over the entire section except very close to the wall of the orifice as shown in Fig. 16. These tests also showed that the tube can be located a little distance beyond the mouth of the orifice and still register correctly. Tests on a 4″ diameter orifice showed that the tip of the tube could be held 2″ from the mouth of the orifice and the dynamic pressure reading was the same as when the tip of the tube was held in the plane of the opening. Tests on larger orifices were not made and there is no reason to believe that the reading is correct for all sizes when the tube is one half the orifice diameter beyond the mouth of the orifice, but it is evident that the tube need not be located directly in the plane of the opening.

Care must be taken, however, that the tip of the tube does not extend into the orifice for full velocity is not attained until the flow reaches the straight part of the orifice and this straight part is usually very short on a properly constructed orifice.

The fact that the orifice will straighten the flow into parallel stream lines, makes it possible to use this combination nearer to bends and fittings than where the orifice alone is used.

In calculating the volume of gas flowing from the Pitot tube reading, it must be kept in mind that the tube gives the actual velocity in the orifice, that is, the velocity of approach plus the velocity due to the pressure drop. Hence, in this case the velocity of approach does not cancel the orifice coefficient as shown under Standard Orifices and the volume as calculated from the Pitot tube reading must be multiplied by the orifice coefficient. This takes care of the falling off of the velocity close to the orifice walls as shown in Fig. 16.

The Hydro Meter

Fig (17)

In all of the above methods described for determining the volume of gas flowing in pipes, the quantity to be measured is the dynamic head, and the question arises as to how this can best be done.

The ordinary U tube filled with water will hardly answer the purpose because close readings are impossible and the instrument is indicating and not recording. The inclined tube gage is accurate enough and close readings can be obtained but it has certain disadvantages which make it undesirable for general use. It is difficult to keep it filled to the proper level and it also must be held in exactly the right position to register accurately. It is very slow in coming to rest after a change in pressure and it is only an indicating instrument, precluding the possibility of securing permanent and continuous records which are so valuable in determining and checking the operation of the plant.

The instrument which meets all the requirements without any of the above disadvantages is the "HYDRO."

The construction of the Hydro Gas Meter is based on the hydrostatic principle. The interior of the vessel is sealed against the atmosphere. Communication between the gas main and the apparatus is established by two pipes, one leading into the space below and the other into the space above the movable bell. Each of these pipes is provided with valves which are linked together to obtain simultaneous operation.

The movement of the bell depends upon the pressure difference above and below the bell. This movement is transmitted to the outside recording drum by a small rod. The latter is encased in a tube leading from the outside of the vessel and ending under the water, thus making use of the water sealing principle for bringing the movement to the outside of the instrument. A pen is attached to the end of the rod and the vertical motion of the bell is registered on a chart fastened to a recording drum. The motion of this drum is obtained by a dust proof clock movement mounted on top of the instrument cover.

The operation of the instrument is practically frictionless hence it is quick to respond to

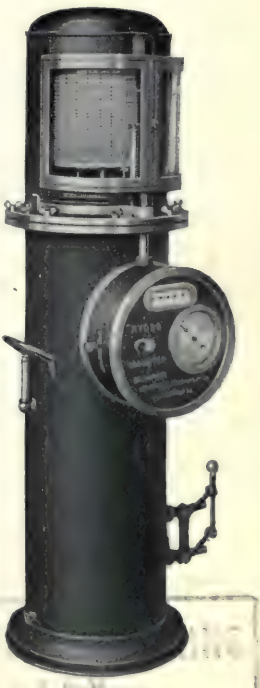


Fig (18)

any changes in pressure. Any desired magnification of the differential pressure can be obtained, instruments having already been built with a magnifying power of 50 to 1, thus making it possible to measure accurately very small pressure differences on a scale large enough to permit of close reading.

The chart can be graduated to read differential pressure in inches of water or rate of flow in cubic feet in a given time. If it is desired to know the total volume of gas which has passed in a given time, it can be found from the chart by finding the average rate of flow and multiplying by the time.

However each instrument can be equipped with an independent integrating device which is attached to the instrument shown in Fig. 18. The power required to operate the integrator is furnished by an independent clock movement, hence, the accuracy of the instrument is not impaired by the addition of this device. A properly graduated dial is also furnished so that the instantaneous volume can be read. Any of the standard Hydro meters can be equipped with this integrator.

Fig (19)

Charts

Charts for the Recording Volume Meter can be made to meet any condition and to read in any units desired. However, it is not practical to make a special chart for each installation so a standard form has been adopted for the volume meter. This chart is 8″ high, makes one revolution in 24 hours and is graduated from 0 to 100. A factor is furnished with the chart, by which the readings are multiplied so as to give the volume in any units desired. In order to calculate this factor, it is necessary to know the average conditions of the gas at the point of measurement and in what units the volume is desired.

Any change from the average conditions of the gas at the point of measurement will mean a change in the calculated factor and in order that the operator may always be able to find the correct volume under the varying conditions, suitable curves are furnished so that the proper correction can be made. In nearly all cases in practice, the only variation in actual conditions of any importance is in the temperature. If this is the case, the factor furnished with the chart is corrected by multiplying by the square root of the ratio of absolute temperatures. After an installation has been made and the standard chart used until all the conditions become well known, then, if so desired, a chart will be furnished to read directly in the desired units.

Comparison

It is not out of place, in conclusion, to draw a comparison between the meters most commonly used in practice, viz., the Hydro, the Venturi, the Thomas and the Wet meter. The principles employed in the Hydro, Venturi, and Thomas Meters are mathematically correct. The Wet meter is purely a displacement meter and its entire operation is mechanical. The Venturi meter is very correct when used properly, and causes very little loss in pressure, because a large part of the induced velocity is converted into pressure again in the diverging tube, but it has the following disadvantages:

It is expensive to construct because the inside walls of the entire tube should be finished to reduce friction as much as possible. Being much longer than any of the devices mentioned in connection with the Hydro meter, it requires more space to install, and this often precludes its use.

It is difficult to keep the walls of the tube clean when measuring dirty gas and any accumulation on the walls increases the friction and changes the area of the throat section. The Venturi meter cannot be used for measuring gases containing tar without the use of a steam jacket or other heating element over the entire length of tube which is expensive to install and operate and necessitates taking the temperature of the gas in the tube itself.

The Thomas meter has the great advantage that its results are entirely independent of eddy currents and as a laboratory instrument, it leaves nothing to be desired but in the practical field it has certain disadvantages.

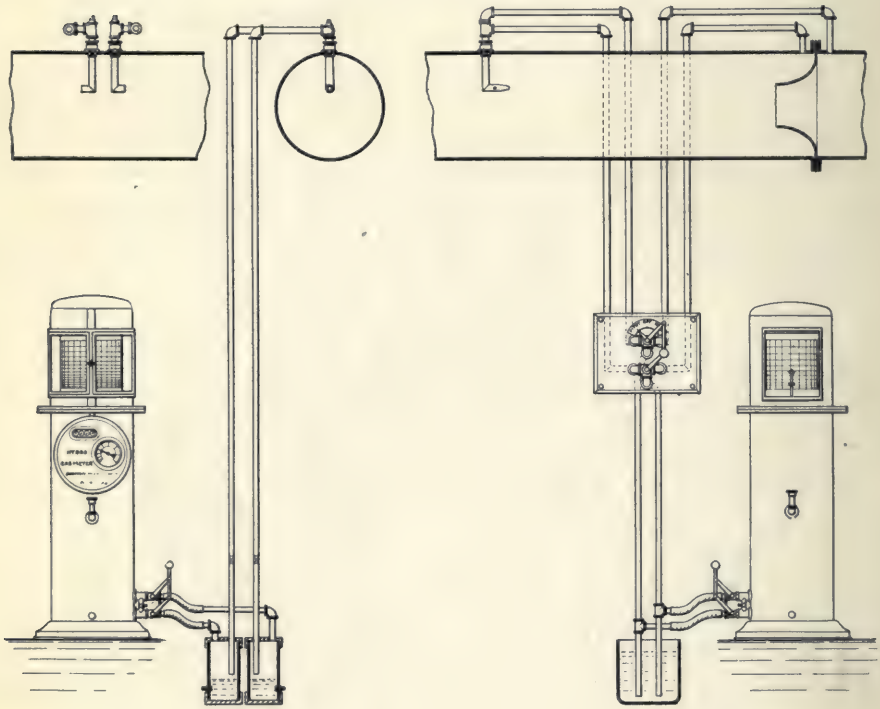
It is probably the most expensive meter made. It requires electric current to operate which means a continual expense. If any entrained water is carried along with the gas, an error will result. Deposits of dust and tar on the heating elements and thermometers will produce an error. The accuracy of the meter depends largely upon the accuracy of the instruments used in measuring the current supplied, so that it is necessary to check these instruments frequently with instruments of extreme precision.

The Wet meter is not as objectionable when measuring a small quantity of gas as when measuring large quantities. In the latter case, the meter becomes very large and expensive. To insure accuracy, the water in the meter must be maintained at the proper level at all times. This is rather difficult when the water expands and contracts due to changes of temperature. The rotating element must be as free from friction as possible and it is very difficult to prevent corrosion, thus causing an inaccuracy. The meter is not adapted to measuring dirty gases. The gas leaves the meter saturated with water vapor which is often very undesirable.

The Hydro meter in combination with the Pitot tube, the thin plate orifice, the standard orifice, or the standard orifice and Pitot tube, is inexpensive to make and install. It requires very little space. After

the meter is installed there is no further expense. There is very little loss in pressure (in case of Pitot tubes, none). The gas may be clean or dirty. It does not change the composition of the gas in any way. The meter requires very little attention and a small change in the water level has no effect on the readings. The operation of the meter can be checked in a few minutes by closing the valves in the connecting pipes and noting if the pen returns to zero. There is no trouble from corrosion, for the meter is made entirely of copper and brass.

Since the principles employed are absolutely correct and have been proven so by countless experiments, the accuracy of the Hydro meters is unquestioned.



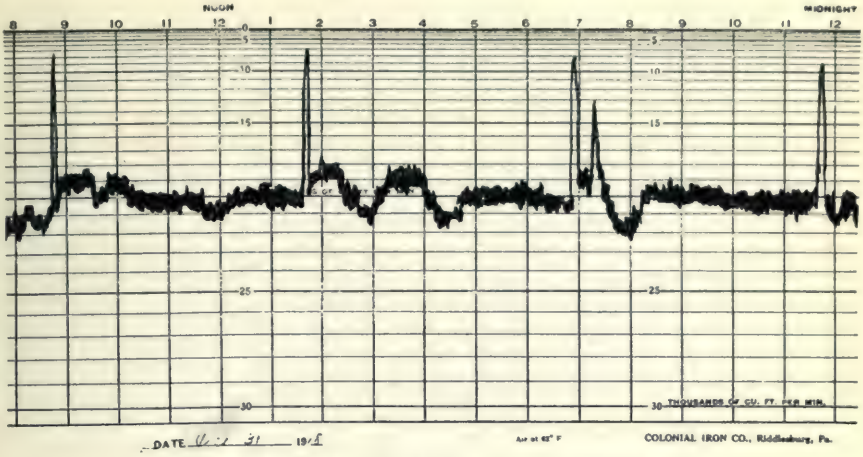
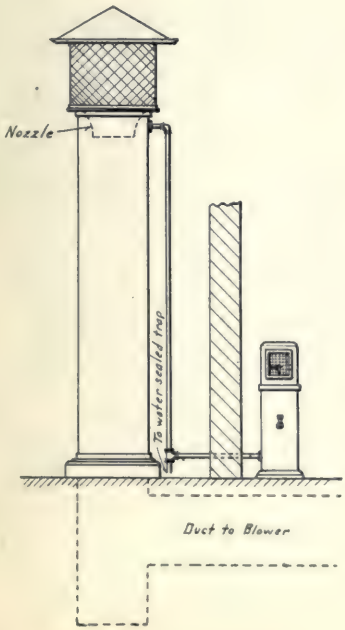


Chart record from Air meter installation at Colonial Iron Co., Riddlesburg, Pa.



Nozzle used in Air Meter installation

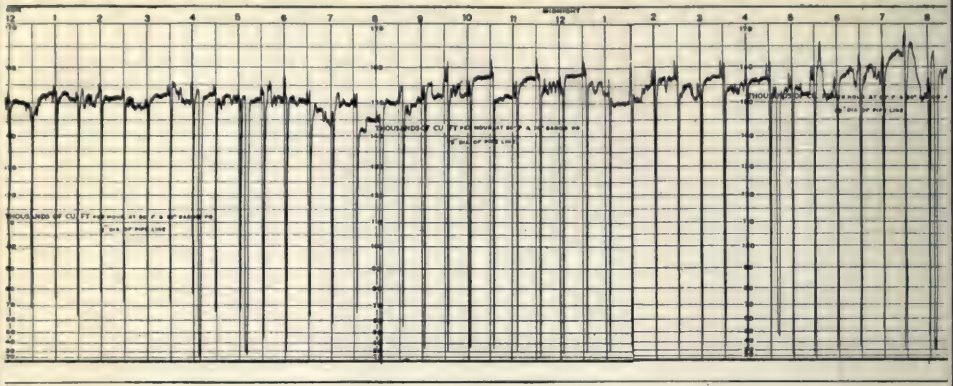
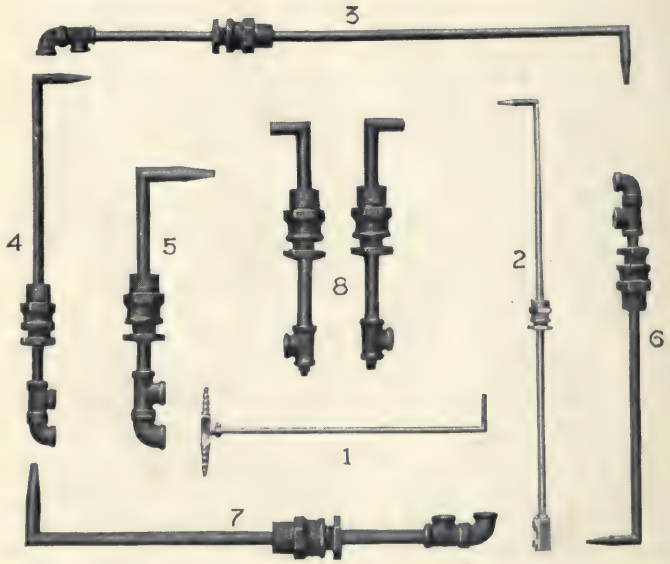
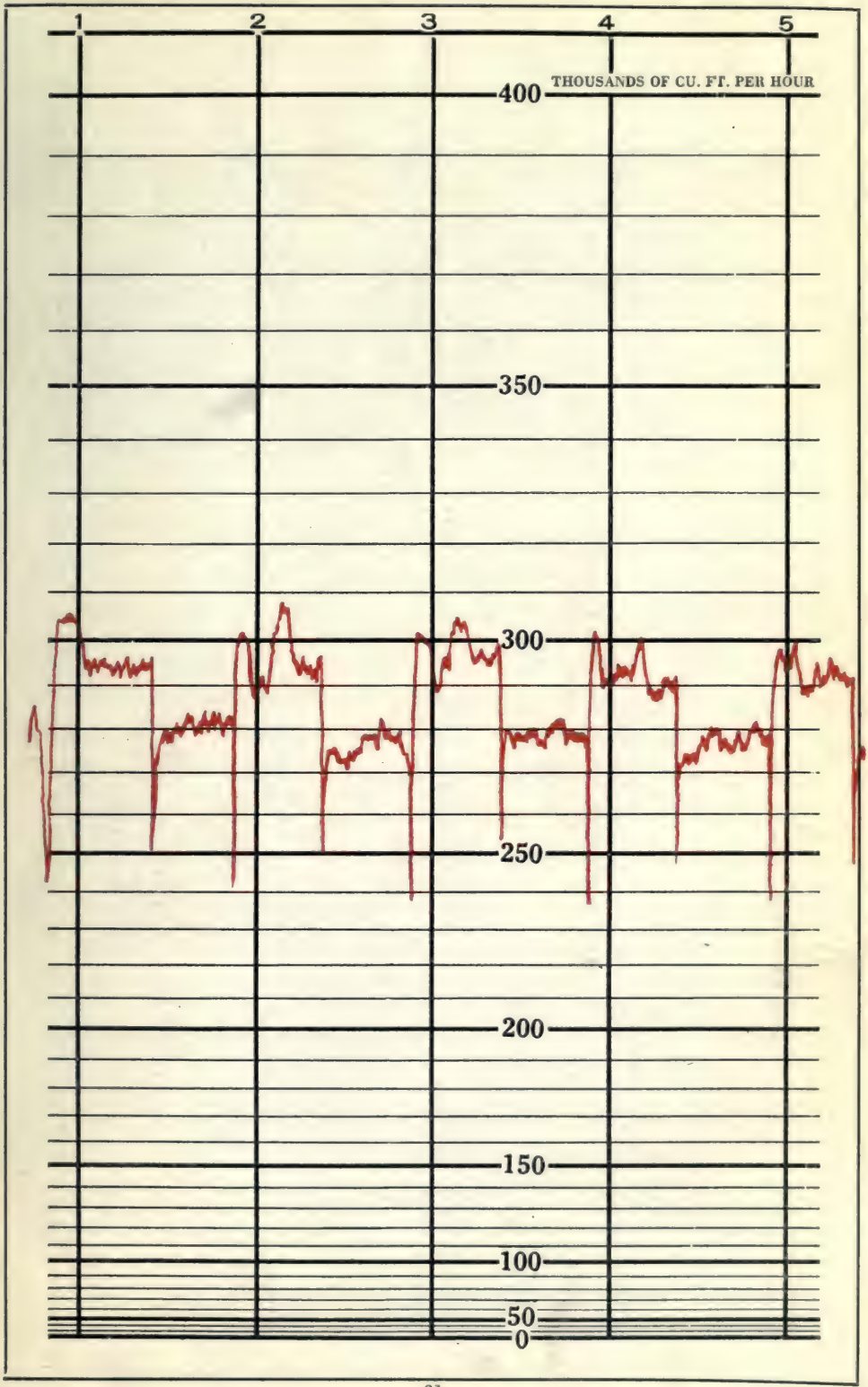


Chart showing amount of Blast Furnace Gas used for Heating Stoves.




1
2
3
4
5
THOUSANDS OF CU. FT. PER HOUR
400
350
300
250
200
150
100
50
0

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